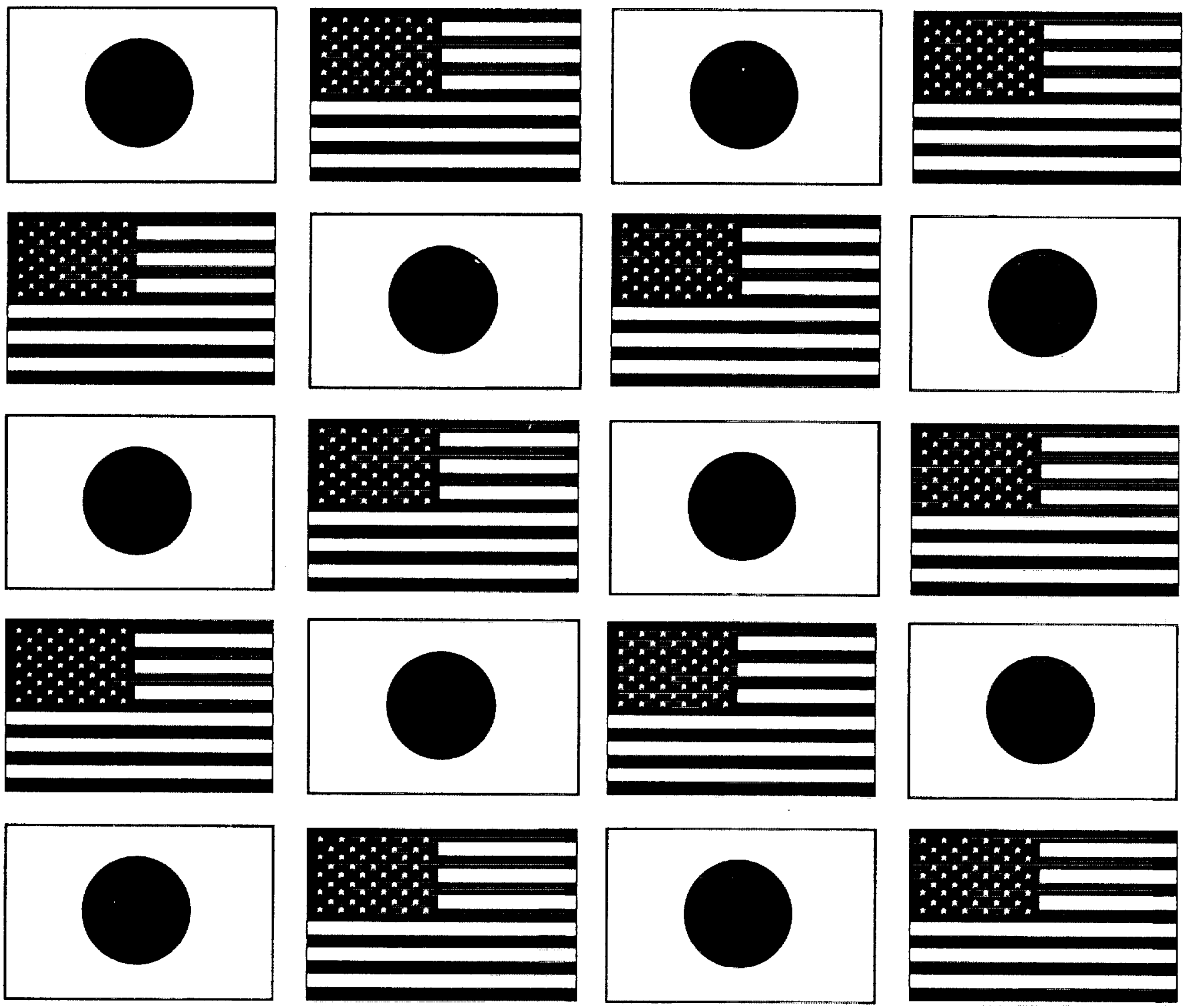
Wind and Seismic Effects

Proceedings of the 30th Joint Meeting

NIST SP 931



U.S. DEPARTMENT OF COMMERCE
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Wind and Seismic Effects

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PROCEEDINGS OF THE 30TH JOINT MEETING OF THE U.S.-JAPAN COOPERATIVE PROGRAM IN NATURAL RESOURCES PANEL ON WIND AND SEISMIC EFFECTS

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EARTHQUAKE ENGINEERING

Analysis of Sea-Floor Earthquake Data

by

Charles E. Smith[1] and David M. Boore[2]

ABSTRACT

The Minerals Management Service (MMS), in cooperation with several oil and gas companies, installed a seismometer network on the ocean floor in the Santa Barbara Channel off the coast of southern California. The program was called SEMS, for the Seafloor Earthquake Measurement System. The purpose of the program was to characterize the nature of the response of earthquake ground motions for use in the design and reassessment of offshore platforms used in petroleum drilling and production. The United States Geological Survey (USGS) was given a contract to provide seismological analysis of data obtained from the SEMS program and compared it to data from earthquakes measured onshore. This paper provides an overview of the work by the USGS on this initiative.

KEYWORDS: earthquake ground motions, offshore platforms, seafloor seismic measurements, seismological analyses, seismic-hazard uncertainties.

1. INTRODUCTION

A major effort was undertaken by both the Government and the oil and gas industry to obtain records of earthquake seafloor motions for the design of new platforms or in the reassessment of the integrity of existing offshore facilities. The prime goal of the program was to obtain data that might help answer the question of whether ground motions at offshore sites are significantly different than those at onshore sites; if this is true, then the decision of using onshore motions as the basis for the seismic design or reassessment of offshore platforms should be reevaluated. This paper provides an overview of the more detailed analysis presented in Boore (1997), Boore and Smith (1998) and Boore (1998) of earthquake data obtained from seafloor seismic motions measured from the SEMS program.

2. SHORT HISTORY OF SEMS.

To obtain creatable data on the response of the seafloor to earthquake-induced ground shaking, the Sandia National Laboratory was commissioned, with funding by the MMS and several major oil companies, to develop, deploy, and recover data from instruments placed on the seafloor. A complete history of the SEMS program is contained in Reece, et. al (1991), Steefe and Engi (1987), Smith (1991), and Platzbecker (1997). A brief synopsis of the SEMS project is provided as background for this paper.

The SEMS program was developed in a number of stages beginning some 20 years ago. These are usually referred to as SEMS I, SEMS II, SEMS III, and SEMS IV (in this paper standard numbers are used rather than Roman numerals; thus SEMS 1, SEMS 2, SEMS 3, and SEMS 4 or more briefly, S1, S2, S3 and S4). The programs were very unique in that all stages of the SEMS project used digital reading of seafloor accelerations. Data were analyzed from S1, S2, and S4.

SEMS1: In 1978, a 3-axis accelerometer was embedded several meters below the seafloor, and the output from the accelerometer was fed to a self-contained instrument package resting on

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the seafloor. This package digitized the input at a rate of 100 samples per sec and stored the data onboard. Data recovery was via an acoustic uplink to a ship deployed specifically for data recovery. The SEMS was installed at several offshore locations and at one onshore location. Data were analyzed from the onshore location (S1VC) and a nearby offshore location (S1HN) near platform Henry in the Santa Barbara channel (See table 1 for station information, and table 2 for earthquake information).

SEMS2: In 1985, the system was redesigned to have a longer system life, and was deployed near platforms Elly and Ellen, off Long Beach. In other respects, the system was similar to that of SEMS1 (a triggered system with data storage in a unit on the seafloor, using an acoustic uplink from data retrieval). The notation "S2LB" was used for this system. Data were analyzed for two earthquakes occuring in 1986, the North Palm Springs and the Oceanside earthquakes.

SEMS3: In 1989, the system was again redesigned, using better batteries, electronics, and triggering algorithm. The result was a longer-life, more sensitive system with fewer false triggers. A major improvement is in using data from horizontal as well as the vertical component in the triggering algorithm (the SEMS1 and SEMS2 units used only vertical component, which, generally has anomalously low amplitudes of motion). The system was deployed at two locations, one near the SEMS2 package off Long Beach (S2LB), and another off of Point Pedernales, near platform Irene (S2IR). This latter site used a datalogger onboard the platform, connected via a cable to the sensor, which was embedded in the seafloor. Apparently the hole did not slump in, and this, combined with cable drag due to strong currents, limited the usefulness of this installation. The only data from a SEMS3 unit used in this paper are that from the 1990 Upland earthquake recorded on S3LB (the recordings for this event, however, are very high quality and useful; they have a long enough duration and a good enough signal-to-noise ratio to record late arriving long-period surface waves.) Unfortunately, recordings of the 1992 Landers earthquake and aftershocks were lost because the seafloor data acquisition system had been dragged away, apparently by a fisherman's net. This is very unfortunate because the earthquake was one of the largest to have struck southern California since 1952. The long-period motions of most concern to platform design were very strong for that earthquake and, as a result, they were well recorded on conventional strong-motion instruments onshore, thus providing an excellent set of onshore motions against which to check the offshore motions (this has been a problem with most of the SEMS recordings: the earthquakes were far enough away and of low enough magnitude that conventional onshore strong-motion recorders either did not trigger or did not record signals that could yield reliable long-period information; in constrast, the SEMS unit can faithfully record these weak motions).

SEMS4: To address the problem of data recovery from stand-alone sea-floor installations, it was decided to deploy a new system in 1995, SEMS4, using a commercial 24-bit datalogger on a platform, with a cable connecting the sensors to the datalogger. The dataloggers also have a dial-up capability, making it possible to interrogate the units remotely. The loggers are being run at 20 samples per sec. The sensors are force balance accelerometers, almost flat to acceleration between 0.4 and 1500 Hz (the response at 1 Hz is nominally down by 3 db relative to the 100 Hz response); the low frequency rolloffs starts at about 0.4 Hz. Three systems have been deployed, near platforms Eureks (S3EU), Grace (S4GR), and Irene (S4IR). Records of earthquakes in 1995 and 1997, recorded by S4GR and S4IR, are analyzed in this report. The SEMS4 instruments have been turned over to the California Strong-Motion Program of the California Division of Mines and Geology, who will operate the stations and collect and disseminate the data. See figure 1 for the layout of the SEMS4 instrument array.

3. ANALYSIS OF DATA

Because of the lack of onshore data for distances comparable to those from the source to the SEMS sites, the empirical interpretation of the data focused on the ratio of response spectra for the vertical and horizontal components (V/H) as a function of period. Comparisons to the few available ratios and to the ratios derived from regression analysis of strong motion data clearly show the offshore ground motions to have anomalously low ratios for short-period response. Some evidence is presented that the anomalous V/H at shore periods is due to very low values for the vertical component. The differences between the average onshore and offshore ratios become smaller as the period increases, but still persist at periods as long as 2 sec. A preliminary study suggests that the differences at the longer periods are more a function of the average shear-wave velocities under the site than to whether the site is offshore or onshore.

To augment the data, theoretical calculations were performed of wave propagation in earth models simulating the offshore environment. Comparisons of observed and theoretical V/H for fouier spectral amplitudes are in reasonable agreement. The theoretical calculations show that the water layer makes almost no difference to the horizontal components of the motion, although it does influence the vertical components of the S-wave portion of the ground motion at frequencies related to the depth of water (around 6 Hz for depths of 60 to 70 M); the effect is negligible for periods near the resonant period of a platform (generally between 1.5 and 4.0 secs). This is not to say that the water is not an important factor, for it does allow relatively low shear-wave velocities to exist over wide regions. There are onshore locations with comparably low velocities, but they are sometimes fairly restricted in spatial extent.

Because of limited recording duration for some of the events, the study was restricted to ground motions less than a 2-sec. period. Recordings for one event, however, were of long enough duration to capture clear long-period (near 6 sec), large amplitude waves, probably surface waves traveling through the Los Angeles basin. A choice of an upper limit of a 2 sec period effectively eliminates these surface waves from our analysis.

4. SUMMARY OF ACCELEROGRAMS USED

The data used in this report included the largest events recorded on the SEMS units. The stations from which data were obtained are listed in table 1, which contains a short summary of basic information for each station; geotechnical information, and estimates of shear-wave velocity for the sites are discussed in a later section. The earthquakes used are summarized in table 2, and table 3, containing event-to-station distances, and is a convenient summary of which station recorded which earthquakes. Tables containing more details about events and stations are contained in Boore (1997). A map showing the locations of the recording stations and earthquakes is given in -igure 2.

With one exception, each earthquake was recorded on only one of the offshore SEMS stations. The exception is the first Simi Valley, 1997 aftershock of the 1994 Northridge earthquake. This event was recorded on two SEMS4 stations: S4GR and S4IR. The lack of multiple offshore recordings for a given event limits, to an extent, the interpretation of the data.

A more important limitation than the lack of multiple offshore recordings is the relative scarcity of onshore data at sites near the offshore sites (by near, we mean along the same general azimuth from the earthquake to the SEMS site, and at distances as close to the SEMS site as the coastal configuration allows; for the earthquakes listed in table 3, there are generally numerous recordings of ground motions but at epicentral distances much smaller than the epicentral distances to the SEMS stations). As tables 2 and 3 show, most of the SEMS records were obtained from moderate-size earthquakes at distances in excess of 70 km. The standard analog, onshore accelerographs do not have the sensitivity to provide digitizable data at these distances for the earthquakes recorded on the SEMS sites. The only earthquake for which we were able to obtain onshore and offshore data is the Santa Barbara Island 1981 earthquake, which was recorded on three onshore stations, one of which was a SEMS unit installed onshore near the Vic Trace Reservoir. The other two recordings, SC38 and SC51, were obtained on standard analog accelerometers maintained by the University of Southern California (USC).

Several sites recorded different earthquakes, thus allowing a check on the stability of the ratio of motions for the vertical and horizontal components. These sites include S2EE, with two recordings, S4GR, with three recordings, and S4IR, with two recordings. In addition, sites S2EE and S3EE were close to one another, so if counted as one site, three recordings are available for these sites.

5. V/H-OBSERVATIONS

Visually, the accelerograms recorded on the SEMS units look much like those from onshore sites. As an example, figure 3a shows the three components of motion for the 1990 Upland earthquake; because the units have pre-event buffers, the initial P-wave motion has been captured (unlike the records from analog accelerographs), and the P-wave is followed by a clear S arrival, which is followed by a slowly decaying coda or tail. The vertical component is small relative to horizontal components, but it is possible to find onshore records with comparable relations between the components.

The acceleration, velocity, and displacement time series for the 1990 Upland SEMS recording are also shown in figure 3. The acceleration traces are largest near the beginning of the record, and they decay to small motions at the time of arrival of the large amplitude long-period waves. The outstanding features of these figures are the late arriving, long-period ($\approx$ 6 sec) motions on all three components. These motions are not unexpected, for the travel path (Figure 2) traverses the Los Angeles basin, and the waves resemble the surface waves that have been observed to propagate in the basin. In seismological terms, the peak accelerations are probably carried by body waves, while the long-period arrivals are surface waves.

The main goal of the SEMS program was to study the similarties and differences of ground motions on the seafloor to those onshore. Because the earthquakes recorded at the SEMS sites were generally not recorded at nearby onshore sites, it is difficult to make a direct assessment of the agreement between onshore and offshore motions; ground motions depend on many variables, such as earthquake size and type of faulting, distance from the source, propagation path, and local site geology, and a comparison of only a few recordings is worthless unless adequate corrections can be made to remove these influences on the amplitudes of the motions. The ratio of vertical to horizontqal motions (V/H), however, might be expected to remove all but the effect of local geology, at least to first order. By comparing ratios, it would then be possible to compare a few onshore and offshore recordings to see if they were comparable or not. This technique was performed in the study. The study also compared the ratios from offshore recordings with those predicted from regression analyses based on hundreds of onshore recordings from many earthquakes; this provides a measure of comparison that represents the average ratio for a typical site and earthquake of a specified magnitude and distance. In addition, the study compared the average V/H for offshore SEMS sites to the V/H from a few onshore recordings for which the shear-wave velocities beneath the recording sites are similar to the velocities we estimate to exist beneath the SEMS offshore sites.

Several events were recorded at the same station (table 3). It is interesting to compare V/H for the multiple earthquakes at a given site to assess the stability of the ratio. Similar ratios for different events might suggest that the ratio is strongly controlled by local site conditions, particularly if the events are different magnitude and have different travel paths to the site. Figures 4 and 5 show such comparisons for fourier amplitude spectra and response spectra. We have treated S2EE and S3EE as one site. In these figures, the geometric average of the two horizontal components has been used for the denominator. There is a general trend for the ratios to increase with period, and there is more scatter at short periods than at long periods. The first impression is that there is considerable scatter in the ratios, particularly at short periods. Careful inspection of the figures, however, shows that generally the ratios of V/H from different earthquakes recorded at individual sites are similar to one another; the large scatter is primarily due to site-to-site variations in the ratio (in particular, compare the S2EE and S3EE to S4IR).

The results are first presented from recordings of the 1981 Santa Barbara Island earthquake, which was recorded on an offshore station and several onshore stations. The ratios of 5 percent damped response spectra are shown in figure 6, in which it is clear that the offshore recording (S1HN) has a much different V/H than for the onshore recordings. The difference is largest at short periods and tends to decrease at long periods. The regression-based ratios are in much better agreement with the onshore ratios than with the offshore ratio. It was judged that with the possible exception of SC38, the onshore sites are underlain by materials with higher shear-wave velocities than the offshore site (SC38 is described to be on dune sand in Anderson et al., 1981, whereas S1VC and SC51 are on marine terrace deposits), and, therefore, one would expect the spectral ratios for the onshore sites to be more similar to the ratios from regression-based results than for the offshore site.

A comparison between the regression-based onshore results and the average of the SEMS offshore results is shown in figure 7. For the sake of clarity, the offshore ratios have been combined into a single average, in spite of the site-to-site differences demonstrated earlier; this will make no difference in the overall comparison of observed offshore and onshore V/H ratios. The distance at which the AS97 relations were evaluated was 120 km, which is close to the geometric mean distance of 113 km for the events used in forming the ratio. The regression-based results for C97 were evaluated at the greatest distance-60 km-for which two equations are valid. Also included in the comparison in figure 7 are results from analyses of specific earthquakes (Loma Prieta 1989 and Northridge 1994), as well as results from the SMART1 array in Taiwan. In general, the onshore results are above the SEMS offshore results, and the difference is largest at short periods.

The large difference between average onshore sites and the SEMS offshore recordings at short periods is consistent with the fundings of Sleefe (1990), who made scatter plots of peak accelerations, with horizontal components on one axis and vertical components on the other. Using differenet symbols for offshore and onshore recordings, he clearly found two populations separated in the same sense as we found for response spectra. In addition, Smith (1990) found that V/H for peak acceleration and peak velocity from offshore sites was smaller than for onshore sites, again in qualitative agreement with the findings from the spectral ratios.

6. PEAK MOTIONS AS A FUNCTION OF DISTANCE

The previous figures show a clear difference in V/H at short periods between the offshore and onshore recordings. Is this due to onshore vs.

offshore differences in the vertical or the horizontal components, or both? To answer this question, figure 8 is plotted of the response spectral amplitudes for a few selected periods as a function of distance from the earthquake. Only the 1981 Santa Barbara Island data was considered since both onshore and offshore data are available. For comparison, the regression-based results of AS97 and C97 were included in the figure. From these plots, it is clear that the offshore vertical component is always smaller than the SEMS and USC onshore vertical components (after accounting for the attenuation with distance); the difference is greatest at shore periods. The same is not always true for the horizontal components. This comparison is strong evidence that the very low values of V/H at short periods are due to small values of V, rather than large values of H. A similar conclusion was drawn by Smith (1994), who plotted peak accelerations against distance for vertical and horizontal components (see figure 9).

7. RESULTS OF THEORETICAL ANALYSIS

The program HSPEC96 by R. Herrmann was used to do the theoretical modeling. This versatile program uses wave-number integration to compute the complete wavefield in an earth represented by a stack of laterally-uniform, constant-velocity layers. Our procedure was to generate synthetic seismograms for a specified type of faulting for the earth model of interest, and then to treat the synthetic seismogram as we would an observed seismogram. In most cases, the Fourier amplitude spectrum was computed of the S-wave portion of the seismogram, although in a few cases the P-wave portion was studied. The focal depth used in the model was 10km. The surface waves resulting from this depth will not be as energetic as the basin waves, which are probably generated by conversion of body waves at basin edges. For this reason, it is not claimed that the theoretical modeling includes basin waves. This is consistent with the possible lack of basin waves in the V/H ratios computed from the data (because of the limited duration for some of the SEMS recordings or the presence of noise at long periods).

Comparison of observed and theoretical spectral ratios in figure 10 shows the observed and theoretical V/H ratios of Fourier amplitude spectra. The observed ratios are for the individual SEMS offshore sites, and the theoretical ratios are geometric averages for a range of focal mechanisms. Although they are somewhat model dependent, the theoretical ratios match the overall trend of V/H decreasing with frequency, although they do not predict the precise behavior of the observed ratio at frequencies above about 4 Hz. The ratios at these frequencies are apparently sensitive to details of the site that we are not including in the model. The overall reduction is probably due to refraction of the S-wave toward the vertical, with a resulting decrease in the V/H ratio.

8. CONCLUSIONS

The Seafloor Earthquake Measuring System (SEMS) is a multiphase instrumentation effort that has been in existence for almost 2 decades. The SEMS stations are excellent instruments and have produced high-quality data for a number of events. However, few data are available from which direct comparisons can be made of onshore and offshore motions from the same earthquake recorded at similar distances and for similar site conditions. For this reason, the analysis of the SEMS data has had to use a combination of somewhat indirect observational studies and theoretical calculations to answer the fundamental question: Are earthquake ground motions at the seafloor so different from onshore motions that the more numerous onshore recordings cannot be used for platform design?

The answer to the fundamental question is "It depends." It depends on the component of motion and the frequency of ground shaking. The ratio of vertical-to-horizontal motions (V/H) is clearly much smaller than for onshore recordings at relatively high frequencies (above about 3 Hz). Studies of the vertical and horizontal motions separately suggest that the anomaly lies with the vertical motions.

Theoretical studies show that the reduction of vertical motions can be produced by interactions of S-waves in the solid materials below the seafloor and P-waves in the water layer. These interactions are most important at the resonant frequencies of vertically propagating acoustic waves in the water layer. A reduced vertical component can also be produced by refraction of an incoming wave toward the vertical, such as will occur for shear-wave velocities that decrease towards the Earth's surface. V/H computed from a few onshore sites with shear-wave velocity versus depth similar to that estimated to be beneath the SEMS offshore stations are much different at high frequencies than the ratios from the SEMS stations, suggesting that simple upward-refraction plays a small role in the difference between onshore and offshore motions at the higher frequencies.

The water layer indirectly influences motions by allowing low-velocity sediments to exist over a widespread area, and by increasing the pore pressure in the sediments, which will reduce the velocity in sands and silts.

As noted before, it is easy to get caught up in the complexities at high frequencies, which reflect the water layer as well as local shear-wave velocities. Although some parts of offshore platform systems are sensitive to high-frequency, vertical component waves (e.g., Smith, 1994, Brady, 1993), the motions are mudline motions and are far from the horizontal resonance frequencies of most offshore platforms. More importantly, for design and analysis of platforms, may be periods of motion longer than 1 second.

Particularly useful recordings for the study of long-period motions were made at a SEMS site offshore Long Beach. Comparisons of response spectra obtained from the SEMS instruments with onshore empirical and theoretical calculations, as well as time-domain comparisons with onshore waves that have traveled through the Los Angeles basin, suggest that the seafloor motions at the SEMS site are significantly influenced by late arriving, large amplitude surface waves ("basin waves") at long periods. These waves may be more important for platform analysis and design than the higher frequency waves that are influenced by the water layer. In this sense, the travel path may be more important than the local site conditions.

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Table 1. Station information (see Table 2 in Boore, 1997, for notes)

Code	Lat	Long	WaterDepth(m)	Nearest Platform
S1HN	34.3367	-119.5600	50	Henry
S1VC	34.4033	-119.7150	onshore	located at Vic Trace Reservoir
SC38	33.8233	-118.3567	onshore	
SC51	34.0233	-118.7867	onshore	
S2EE	33.5867	-118.1233	73	Elly/Ellen
S3EE	33.5700	-118.1300	64	Elly/Ellen
S3IR	34.6117	-120.7317	76	Irene
S4EU	33.5617	-118.1167	217	Eureka
S4GR	34.1800	-119.4700	99	Grace
S4IR	34.6117	-120.7300	76	Irene
CM	33.6400	-117.9300	onshore	located in Costa Mesa
PV	33.8017	-118.3867	onshore	located in Palos Verdes

Table 2. Earthquake information (see Table 4 in Boore, 1997, for notes and references)

EqID	EqName	yy/mm/dd	hh:mm	EpcntrLat	EpcntrLong	M
SB81	Santa Barbara Island	81/09/04	15:50	33.66	-119.10	5.95
NP86	North Palm Springs	86/07/08	09:20	34.00	-116.61	6.10
OS86	Oceanside	86/07/13	13:47	32.97	-117.87	5.84
UP90	Upland	90/02/28	23:43	34.14	-117.70	5.63
RC95	Ridgecrest	95/09/20	23:27	35.76	-117.64	5.56
CL97	Calico	97/03/18	15:24	34.97	-116.82	4.85
S97A	Simi Valley	97/04/26	10:37	34.37	-118.67	4.81
S97B	Simi Valley	97/04/27	11:09	34.38	-118.64	4.72
SF71	San Fernando	71/02/09	14:01	34.40	-118.39	6.6

Table 3. Epicentral distances, in km, between earthquakes used in this report and stations recording the earthquakes. SF71 is the San Fernando earthquake; while not recorded on a SEMS unit, the onshore records are used in a comparison with offshore records from other earthquakes.

sta	SB81	NP86	OS86	UP90	RC95	CL97	S97A	S97B	SF71
S1HN	86.0								
S1VC	99.9								
SC38	71.1								
SC51	49.4								
S2EE		147.5	72.5						
S3EE				74.4					
S3IR									
S4EU									
S4GR						258.1	76.7	79.3	
S4IR					309.1		191.2		
CM									94.6
PV									66.4

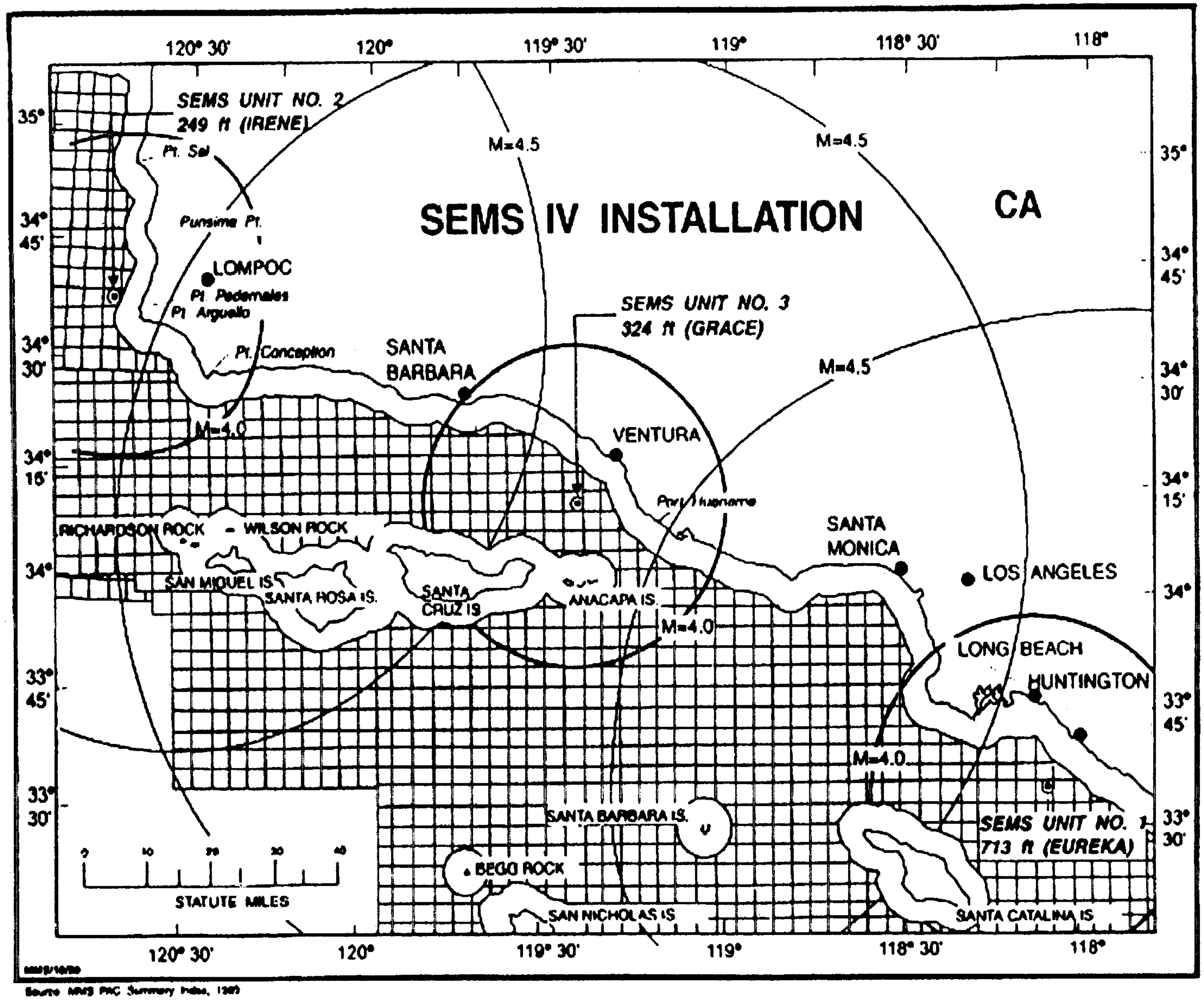

Figure 1. Location of the SEMS IV installation showing areas of measurement of equal magnitude earthquakes.

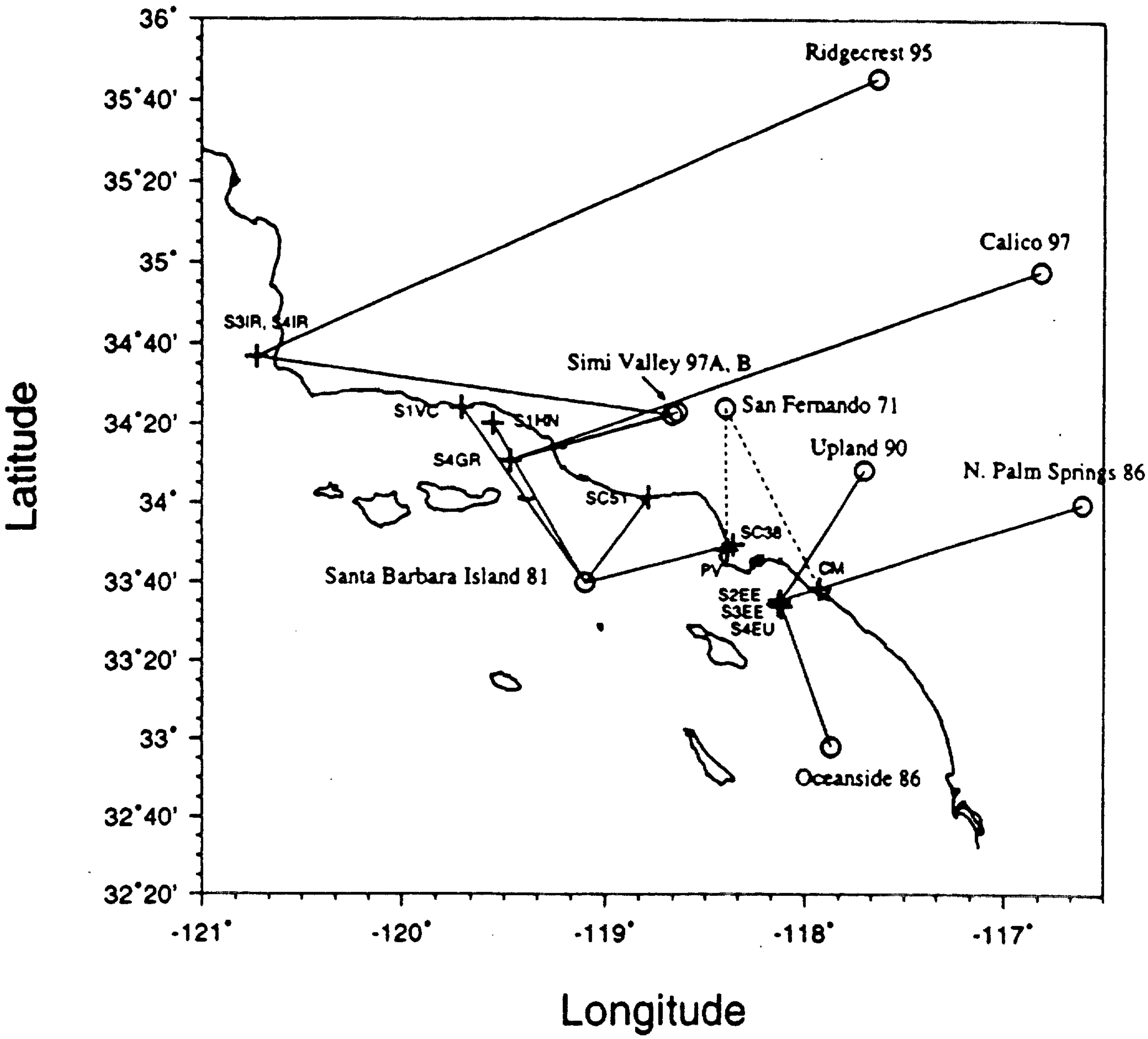

Figure 2. Map of southern California. Lines connect events (open circles) and stations (pluses) providing data for the corresponding event. The dashed lines show paths for two recordings of the 1971 San Fernando earthquake; these paths cross the Los Angeles basin, as does the path from the Upland 1990 earthquake to SEMS site S3EE. Waveforms of these two events are compared in this report. Although providing no data, station S4EU is shown for completeness.

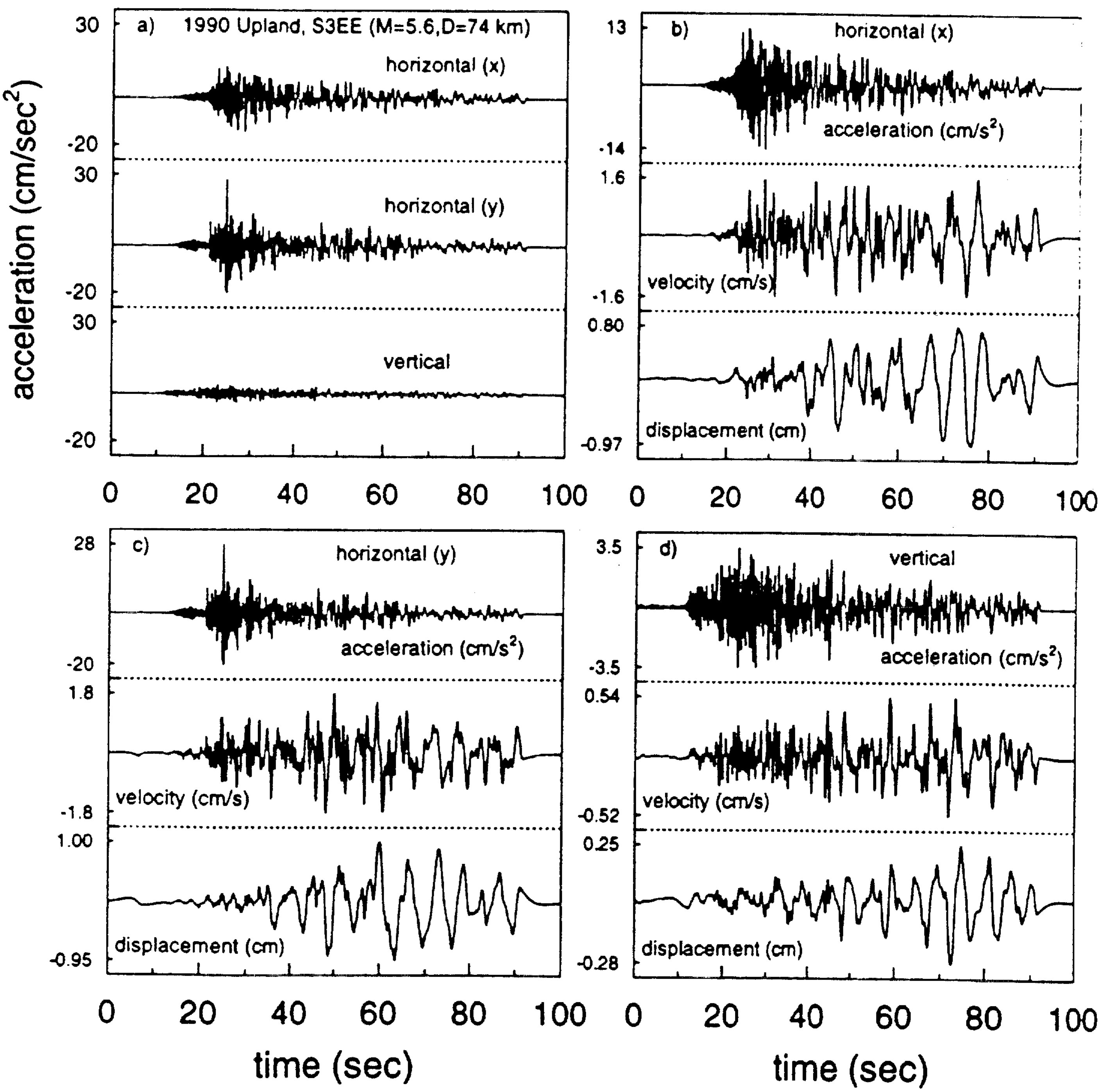

Figure 3. a): Three-component accelerograms, in cm/sec^2, of the Upland 1990 earthquake recorded at SEMS station S3EE, plotted using the same vertical scale to emphasize the relative amplitude of the components. The time series are similar to those recorded onshore, with a clear portion of strong S-wave arrivals following the initial P-waves. Two interesting characteristics are the small amplitude of the vertical motion relative to the horizontal motions and the long-period energy arriving after the portion of strongest ground acceleration. b), c), and d): acceleration (cm/sec^2), velocity (cm/sec), and displacement (cm) time series for the three components of the S3EE recording of the 1990 Upland earthquake, plotted using different vertical scales, to emphasize the appearance of the waveforms. Note the dominance of late arriving 5 to 6 sec waves on the displacement trace, something not emphasized in the accelerogram.

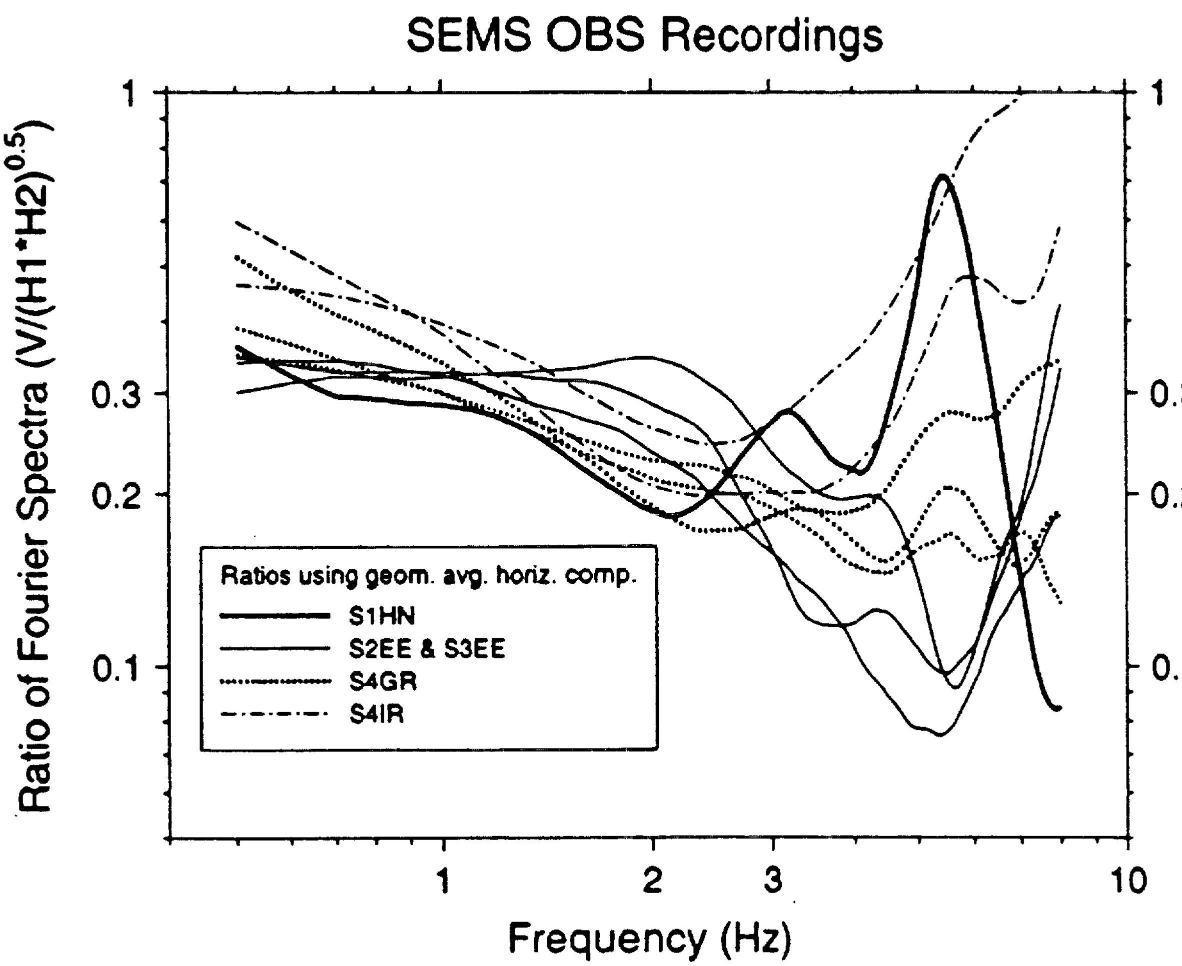

Figure 4. Comparison of V/H ratios of Fourier amplitude spectra for the offshore SEMS recordings through 1990. For clarity, the line type was used for all recordings at a given site, to emphasize the site-to-site variation of the ratios. The ratios for the various recordings at a given site are similar, and all of the ratios are very similar at low frequencies and show considerable divergence at high frequencies. Spectral ratios were computed after smoothing each component with a triangular operator spanning 2 Hz.

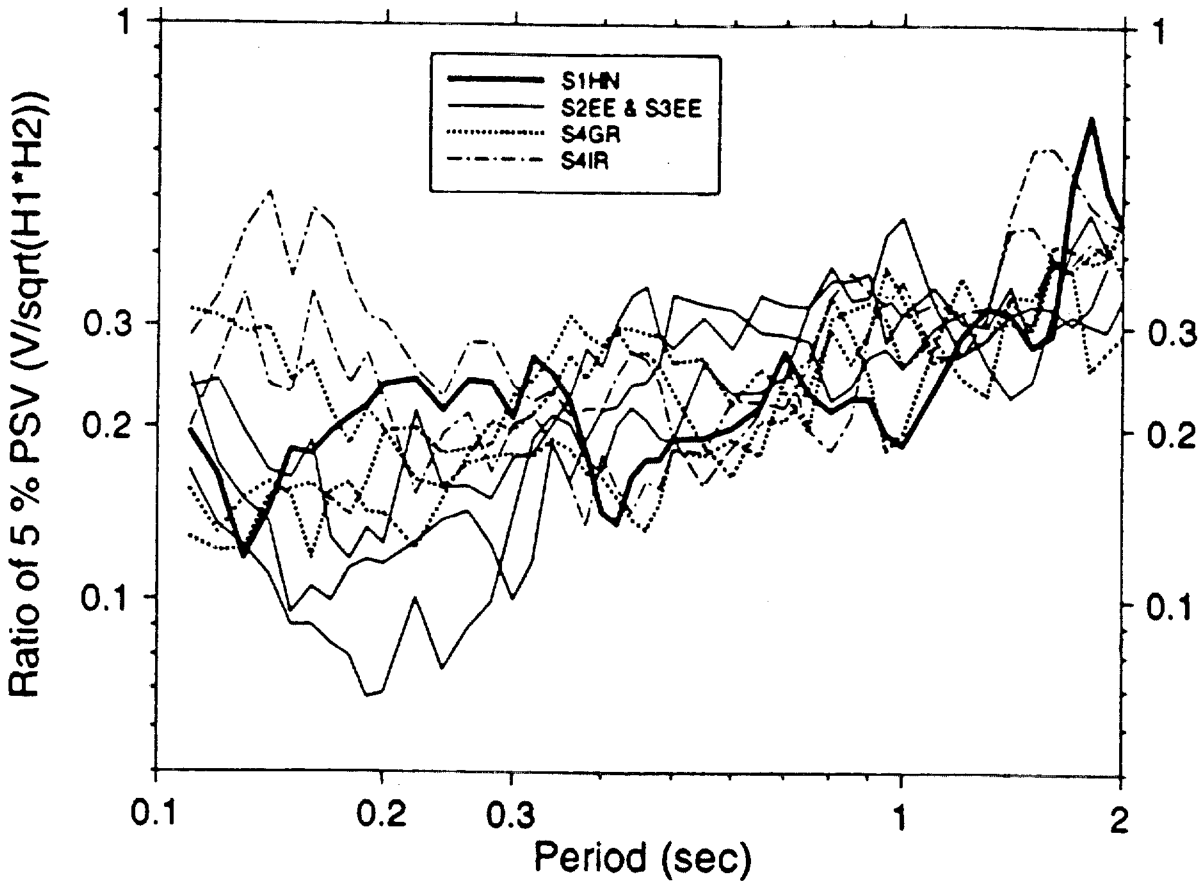

Figure 5. Comparison of V/H ratios of 5%-damped response spectra for recordings at all of the offshore SEMS sites considered in this report. In view of the widespread distribution of the stations, the ratios are remarkably similar, particularly for the longer periods. Theoretical calculations suggest that the spread in the ratios at short periods may be due to site-to-site variations in water depth and near-surface geological properties.

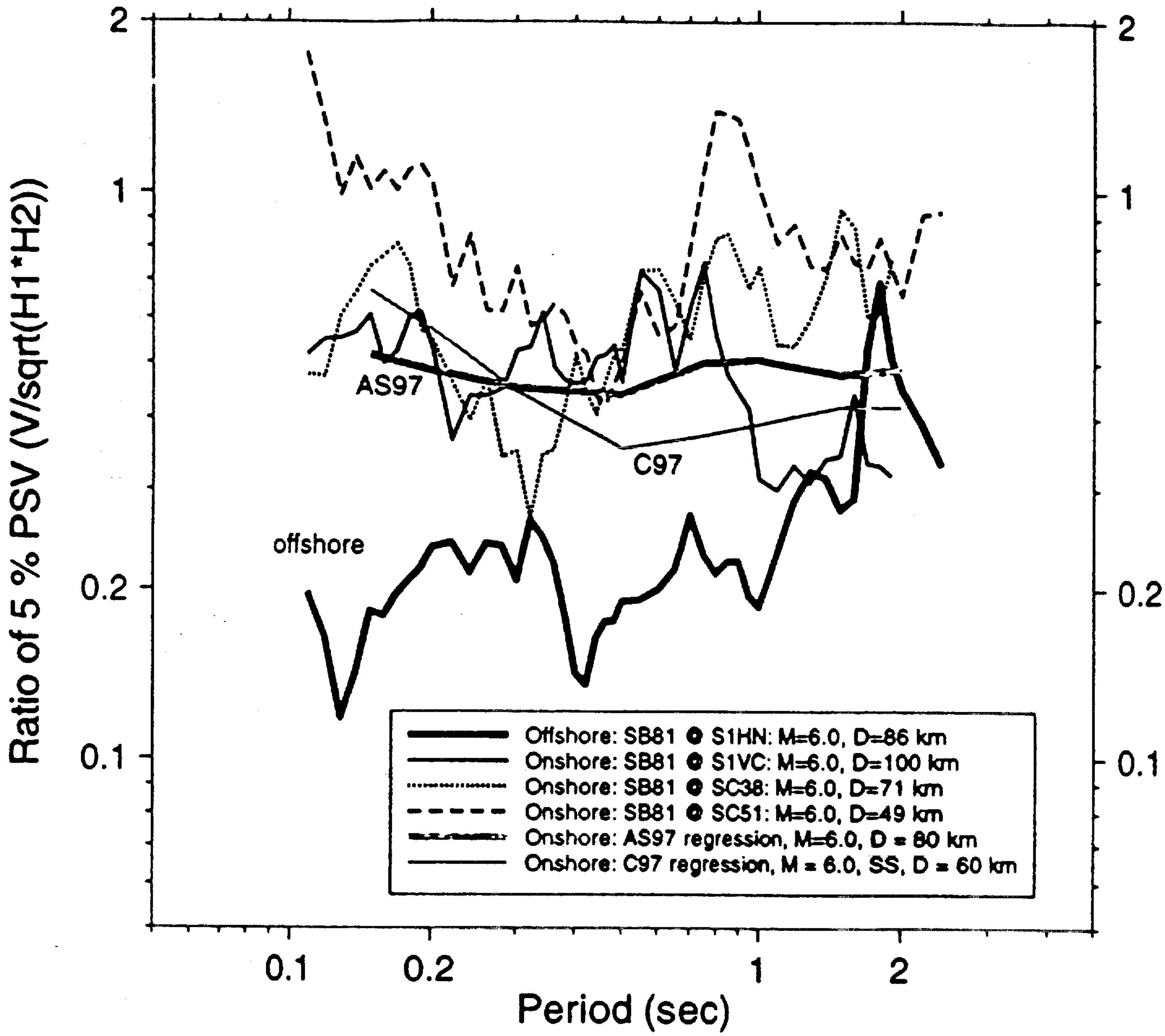

Figure 6. V/H ratios of 5%-damped response spectra for offshore and onshore recordings of the 1981 Santa Barbara Island earthquake, compared with the regression results of Abrahamson and Silva (1997) ($AS97$) and Campbell (1997) ($C97$). The ratio for the offshore site (S1HN) is much lower at short periods than are the ratios from the onshore sites.

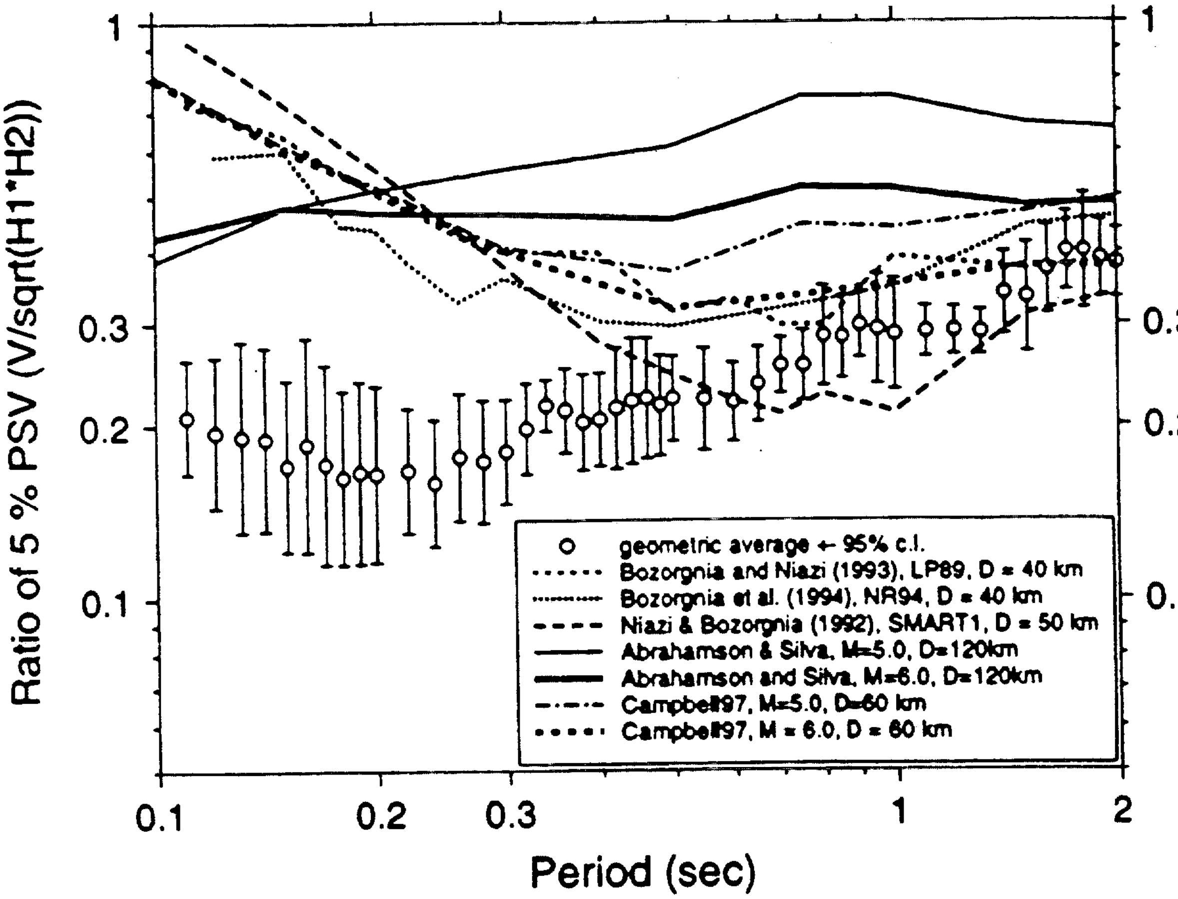

Figure 7. Observed offshore V/H ratios of 5%-damped response spectra (open circles) compared with onshore ratios from regression analyses. The results for the Loma Prieta and Northridge earthquakes are indicated in the legend by "LP89" and "NR94", respectively. The Bozorgnia *et al.* (1994) results for the Northridge earthquake differ slightly from those in the final published study (Bozorgnia *et al.*, 1995).

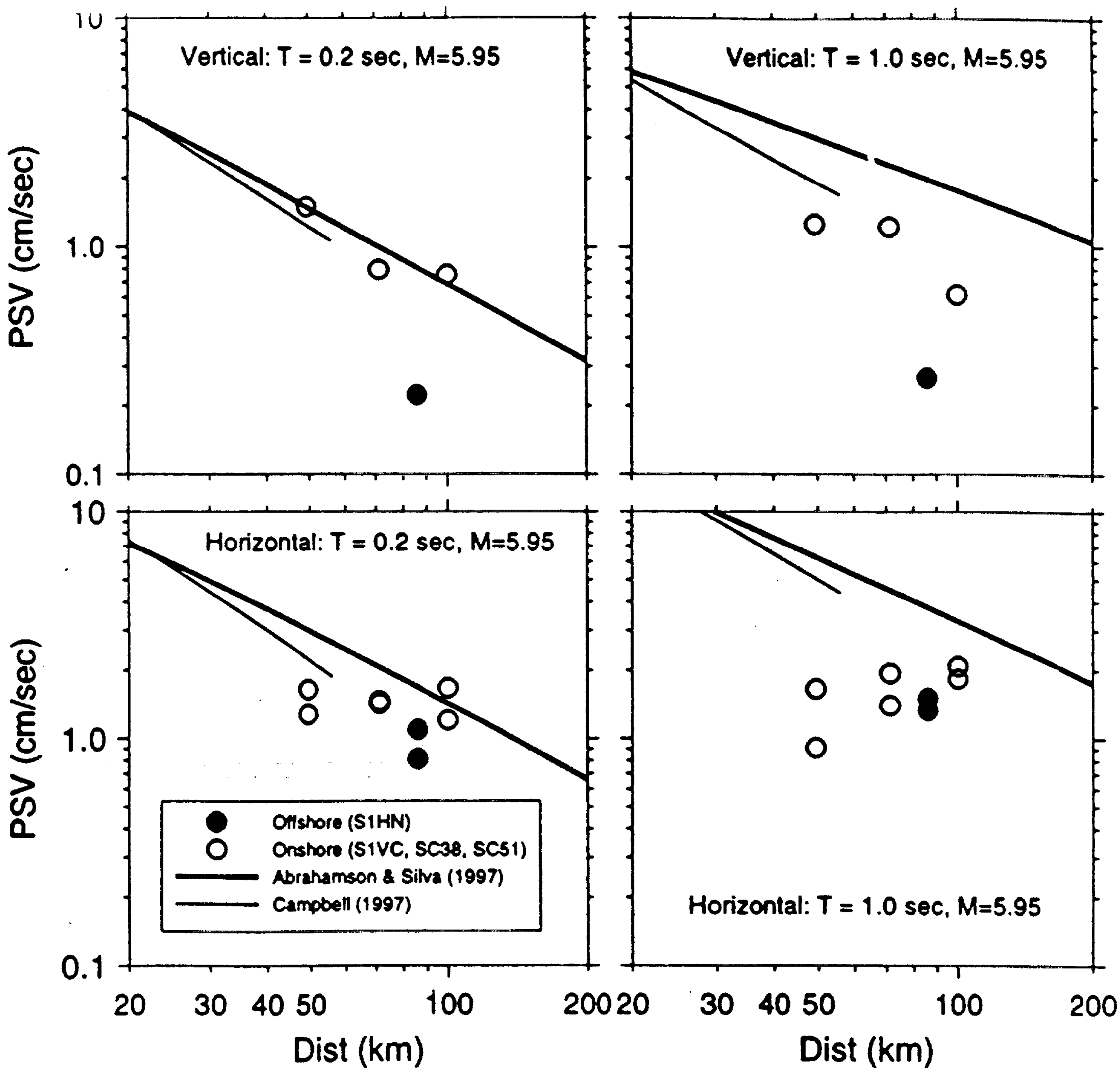

Figure 8. 5%-damped pseudo-velocity response spectra for 0.2 and 1.0 sec oscillator periods as a function of epicentral distance for the 1981 Santa Barbara Island earthquake, compared with predictions from regression analyses. The different symbols differentiate between the offshore and onshore recordings of the earthquake. Note that for the vertical component (top two panels), the spectra from the offshore recording is much lower than the onshore spectra, whereas for the horizontal components (bottom panels), the onshore and offshore spectra are comparable.

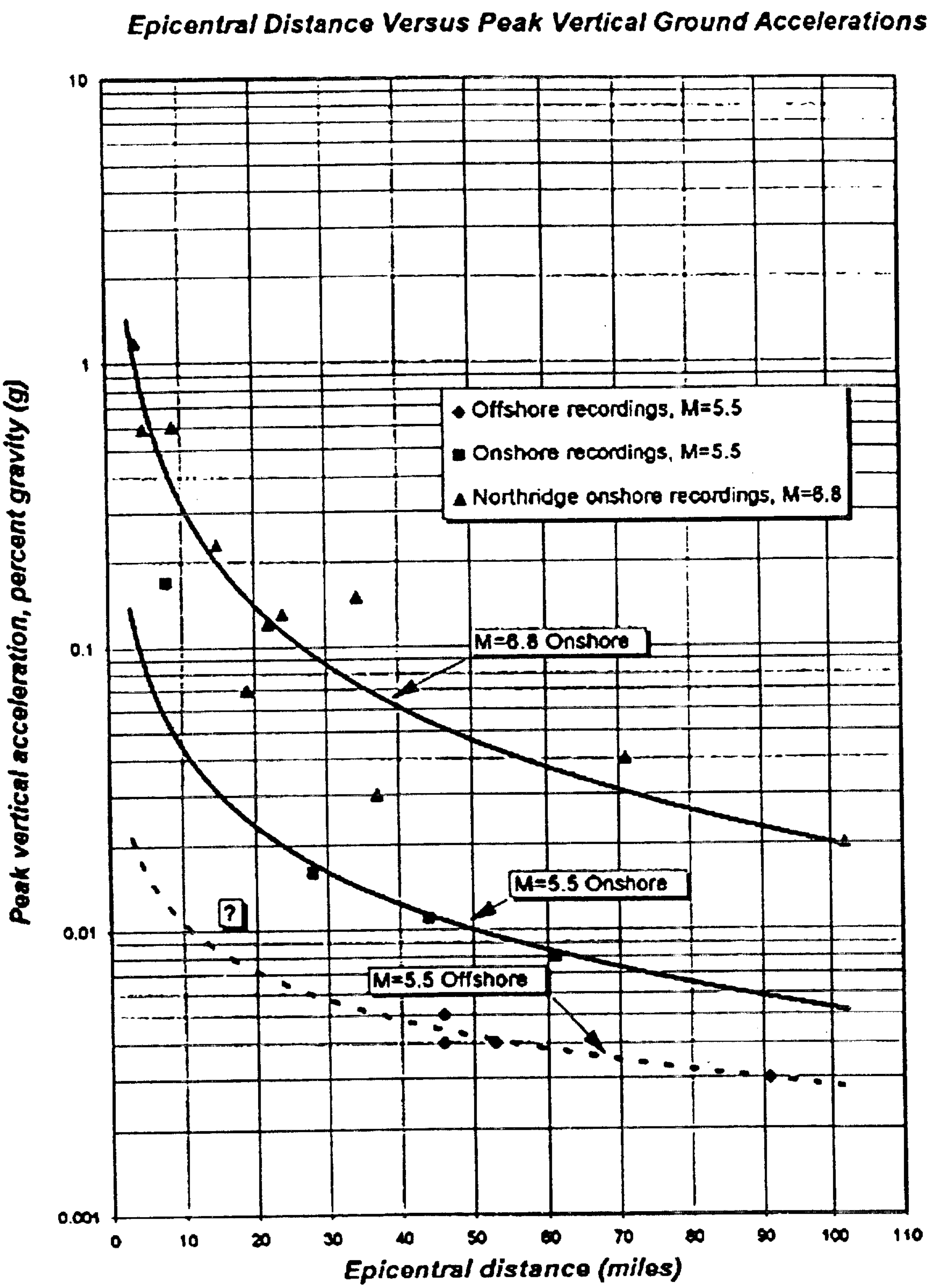

Figure 9. Epicentral distance verus peak ground accelerations

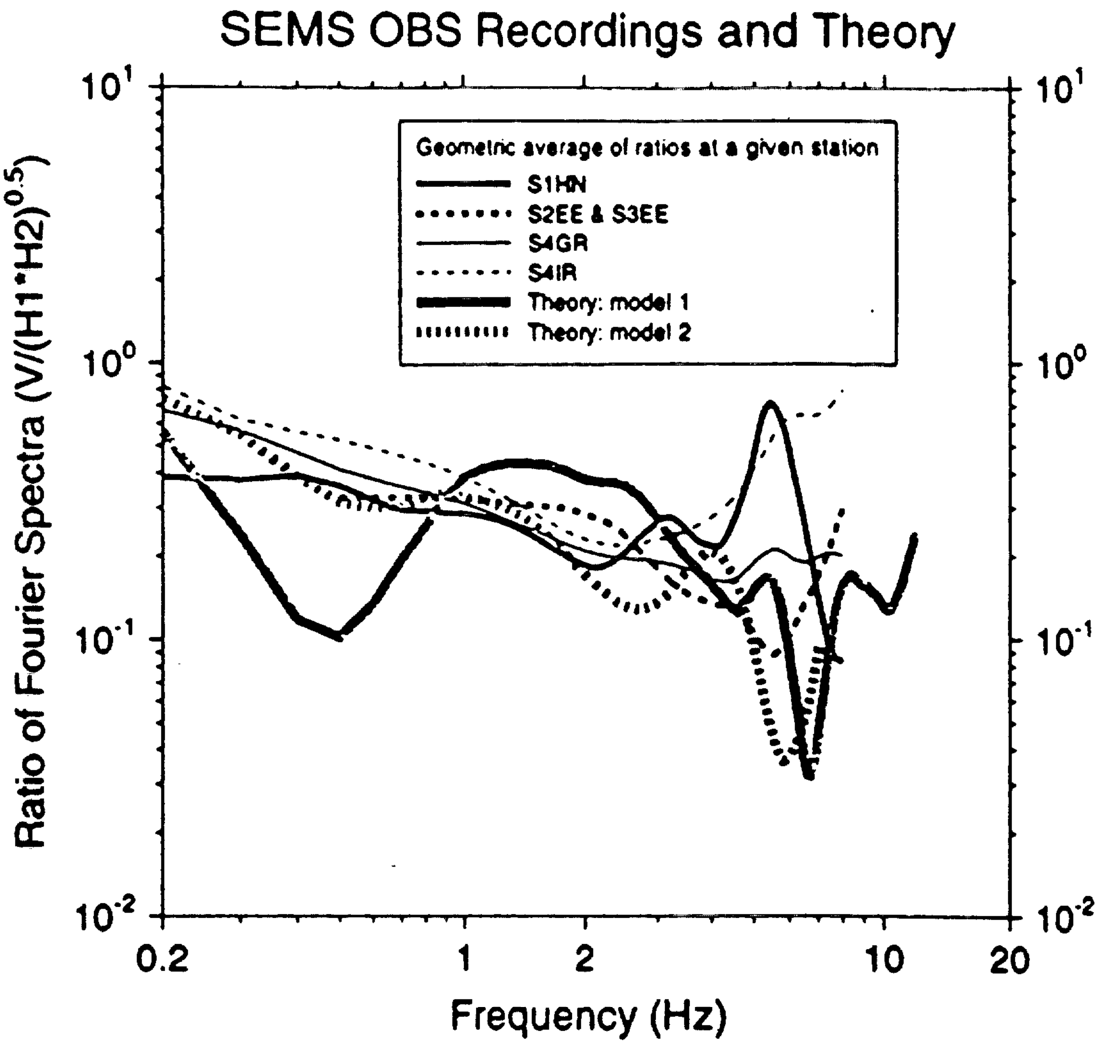

Figure 10. V/H ratios of Fourier amplitude spectra of the S-wave portion of offshore recordings, compared to theoretical predictions.